# Accurate and efficient modelling of grid tied inverters for investigating their interaction with the power grid

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***Abstract*—The power electronic based Grid Side Converter (GSC) is the key technology for interconnecting RES. In order to obtain accurate simulation results, it is important to have a detailed-realistic modelling of GSCs. This requires a very small solver step (i.e., solver period near 1 μs) due to the high-frequency switching operation of these converters. Such a small solver period imposes computational constraints, especially when there is a need to investigate the dynamic power system operation with several installed RESs. This paper proposes a simplified but still very accurate modelling solution for the GSC of RES for performing accurate and dynamic simulations with a significantly larger solver step. A case study is also demonstrated, where the proposed model of the GSC is utilized to investigate the interaction between several distributed RESs (with advanced controllers) and the power grid.**

***Index Terms*—Grid side converter, inverter, modelling, renewables, power system, fault ride through.**

## I. Introduction

The penetration of Renewable Energy Sources (RES) is continuously increasing. An average penetration level of 16% is already achieved in Europe [1], while a particular attention is internationally received by the modern RES, such as Wind Power Systems (WPS) and Photovoltaics (PV), due to their increased competitiveness. The grid-connection of the modern RES is enabled through the power electronic based grid tied inverter, usually referred to as the Grid Side Converter (GSC). Further, the new grid regulations [2] require advanced operational capabilities by the smart GSC of RESs [3] in order to contribute to the maintenance of the quality and stability of the power system. Thus, under a high penetration of RES, there is a need for a detailed investigation of both the power system and the distributed RESs within the same framework.

For investigating the dynamic interaction between the GSC of RESs and the power grid, a proper, accurate and compatible modelling of both the GSC and the power system is required. In the area of power systems, there are two types of models that are usually used for simulations: the Root Mean Square (RMS) and the ElectroMagnetic Transient (EMT) models [4]. The RMS models for power systems are widely utilized [5] and the simulator uses voltage and current phasors expressed in the nominal frequency (50 Hz) and requires a solver period ($T_{solver}$) of 20 ms. Such models are very computationally efficient, especially for large scale systems, but they present a lack of accuracy regarding transient and sub-transient response and they cannot be used for investigating the effect of non-linear loads (i.e., harmonics) in the power grid. Further, the modeling of power electronic based converters is also challenging when RMS simulation models are used. The modelling of RESs based on RMS models is suggested in [6], [7]. Moreover, an HVDC equivalent model founded on circuit theory for the quasi steady-state time scale is suggested in [8] for enabling long term stability analysis. However, these models cannot be accurate under transient events or non-linear conditions (i.e., harmonics, asymmetries) and furthermore, a realistic response of the synchronization method of RES cannot be properly considered in RMS simulations.

EMT models for power systems [9], [10] are time-domain simulations requiring a solver rate 100-400 times faster ($T_{solver}$=50-200 μs) than the fundamental frequency of the power system (i.e., 50 Hz). These models are more computationally heavy but they are more accurate and appropriate for investigating non-symmetrical, non-linear and transient/sub-transient conditions in the power system. Further, full detailed EMT simulation models are widely used for modelling RESs (with their associated GSC) [11], [12]. In these cases, a very high solver rate ($T_{solver}$~1 μs) is required for accurately tracking the realistic operation of the GSC due to the high switching frequency ($f_{switching}=1/T_{switching}$) of the power electronic devices (i.e., $f_{switching}$ is usually in the range of 5-20 kHz). However, the use of such detailed RES models for investigating the interaction between RESs and large-scale power systems as suggested in [2], [4] can lead to extremely computationally heavy models, since the entire simulation model should solve with the highest solver rate for achieving accurate results.

This paper proposes a simplified but still very accurate modelling for the GSC of RESs in order to enable EMT simulations that are compatible for investigating the interaction between RESs and the power system. The prospective of the proposed modelling is to replace the switching power electronics components of the converter with a corresponding average EMT model. The average model considers the realistic

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response of advanced GSC controllers, the expected delays within the converter, the effect of the LC filter, and the DC-link behavior. Thus, the expected line currents at the AC side and the capacitor voltage at the DC side are accurately estimated without any high-frequency switching noise and replicated in the GSC model through ideal current and voltage sources. The proposed GSC can achieve a very accurate response (very similar to the response of the detailed GSC model) under any grid conditions (i.e., change of the power injection, unbalanced grid faults, low-order harmonic distortion). The only issue that cannot be considered by the proposed model is the high-frequency noise due to the switching operation, however this noise is usually neglected as a result of a proper LC filter and DC capacitor design. The significant advantage of the proposed simplified GSC model is the smaller solver rate (i.e., simplified GSC requires a $T_{solver}$ of 50 μs compared to the detailed GSC that requires a $T_{solver}$ of 1 μs) since the switching operation of power electronics is overcome. This fact, enables the use of the proposed models to investigate the interaction between several RESs and the power system with a common and smaller solver period ($T_{solver}$~50 μs), which is much more computationally efficient. Furthermore, the proposed GSC models allow to investigate the effect of advanced control techniques for RESs on the overall performance of the power system.

This paper is organized as follows: the proposed modelling is presented in Section II, the accuracy of the GSC model is evaluated in Section III and the interaction of several RESs with the Distribution Network (DN) using the proposed models is depicted in Section IV. The paper concludes in Section V.

## II. Accurate Modelling of Grid Tied Inverters

The grid tied inverter is the cornerstone for interconnecting RESs into the power grid. The GSCs are based on power electronics technology and thus, the most accurate modelling of the GSC operation can only be achieved based on detailed (but computationally heavy) models (Section II.A), where all the high-frequency switching devices are properly modelled. This paper proposes a simplified GSC models as presented in Section II.B, which can be very accurate under several conditions, be more computationally efficient, and can be used for investigating the interaction between several RESs and the power system.

### *A. Full detailed model for the GSC*

An actual GSC for modern RESs is presented in Fig. 1 and is based on a three-phase voltage source inverter with six Insulated Gate Bipolar Transistors (IGBTs), an LC or LCL filter for eliminating the high-frequency switching harmonics, and an advanced controller for regulating its operation under any grid conditions. In real GSCs, the controller is developed in discrete-time in the embedded micro-controller using a constant sampling period ($T_{sam}$). As shown in Fig. 1, the GSC is mainly based on Phase-Locked Loop (PLL) techniques [13] for enabling the fast and accurate synchronization (estimating the voltage vector $\mathbf{v}$ and its phase angle $\theta_{PLL}$ of the fundamental positive sequence grid voltage) under any grid conditions, on an active and reactive power controller (*PQ* controller) [11], [13] that is responsible for generating the reference currents under normal and Fault Ride Through (FRT) operation conditions (i.e., unbalanced low voltage sag events), and a current controller [14] for producing the reference voltage ($\mathbf{v}_{ref}$)

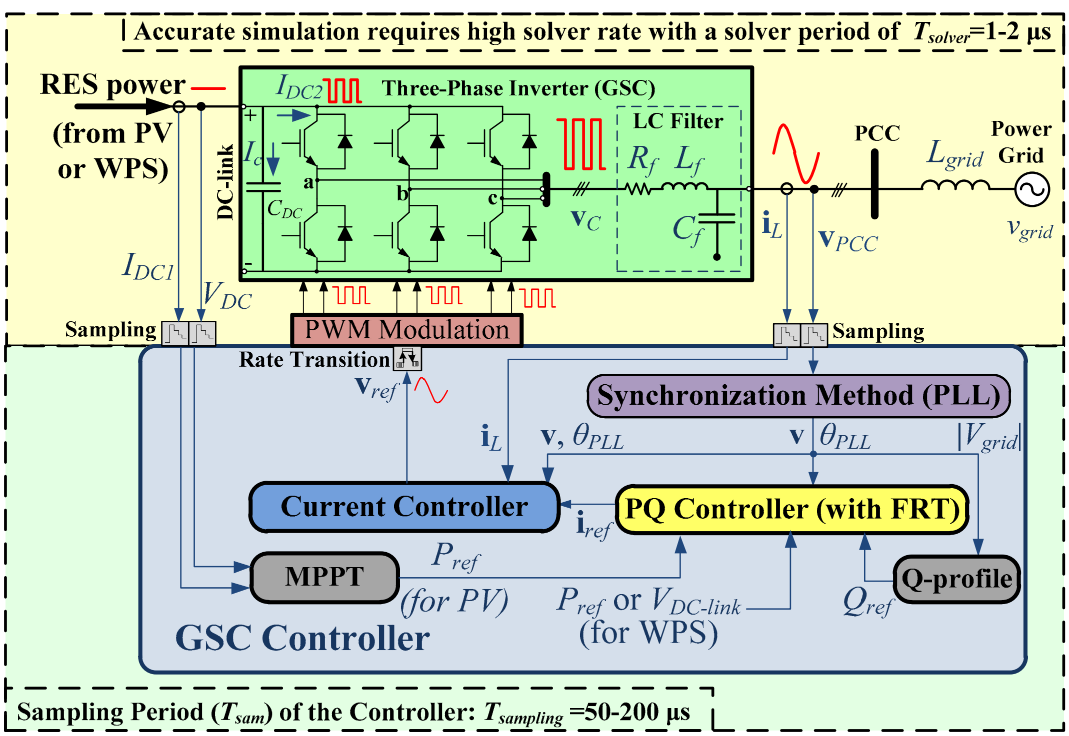


Fig. 1. Detailed model for a realistic grid tied converter of a RES.

that is used by the Pulse Width Modulation (PWM) to generate the pulses for driving the IGBTs of the GSC.

Since this detailed model for the GSC considers the high-frequency switching PWM operation of the power electronics ($f_{switching}$ ~ 5-20 kHz), there is a need to use very small solver steps ($T_{solver}$~1 μs) in these simulations in order to accurately track the operation of a realistic GSC. Such small solver step creates heavy computational requirements for the simulation models. Especially, in case where the interaction between several RESs and the power system needs to be investigated, the entire simulation model (for the RESs and the power system) needs to be solved with this very small solution step. In the next sub-section, a more compatible model for the GSC of RES is proposed, where a significantly larger solver step is needed for simulating both RESs and the power grid.

*B. Proposed simplified model for the GSC*

A simplified model is proposed here for the GSC of RESs, which can accurately track the actual response of the GSC with significantly less computational requirements. For developing such a simplified model as shown in Fig. 2, all the high-frequency switching signals have been estimated using average models. As depicted in the detailed model of Fig. 1, the switching signals are actually the converter voltage vector $\mathbf{v}_c=[v_{ca}\ \ v_{cb}\ \ v_{cc}]^T$ (representing the produced voltage by the GSC for each phase a, b , and c), and the current ($I_{DC2}$) between the DC-link capacitor ($C_{DC}$) and the IGBTs. Therefore, these switching signals are replaced by the corresponding estimation vector $\hat{\mathbf{v}}_c$ and signal $\hat{I}_{DC2}$, which are calculated based on average models for eliminating the high-frequency switching noise. In the real GSC, this noise is actually eliminated by the LC filter and the capacitor $C_{DC}$ and thus, can be negligible in case where the power quality issue related to high frequencies is not to be considered. Similar average models have been used in [15], [16] for designing and tuning the GSC controllers.

For estimating the expected line currents $\hat{\mathbf{i}}_L=[\hat{\imath}_{La}\ \hat{\imath}_{Lb}\ \hat{\imath}_{Lc}]^T$ without any switching noise, it is first required to estimate $\hat{\mathbf{v}}_c$. According to Fig. 2, $\hat{\mathbf{v}}_c$ can be estimated through the transfer function $\underline{G_c}(s)$, which represent the average operation of the PWM hardware peripheral of the embedded micro-controller and the operation of the six IGBTs and is given as,

$$G_c(s)=\frac{\hat{\mathbf{v}}_c}{\mathbf{v}_{ref}}=\frac{1}{1+T_{delay}\cdot s} \tag{1}$$

where $\mathbf{v}_{ref}$ is the output of the GSC before to be fed in the PWM hardware module for generating the IGBTs pulses and $T_{delay}$ represents the delay of the converter. For an accurate model and if no additional delays are imposed when the PWM interrupt is called, then the $T_{delay}=T_{sam}+0.5{\cdot}T_{switching}$ (a sampling period delay due to the sampling of the controller and half switching period until $\mathbf{v}_{ref}$ appears at the GSC output). Then, the expected line current $\hat{\mathbf{i}}_L$ can be estimated through the filter transfer function $G_f(s)$ given in (2) (by ignoring the capacitor effect).

$$G_f(s)=\frac{\hat{\mathbf{i}}_L}{\Delta\mathbf{v}}=\frac{\hat{\mathbf{i}}_L}{\hat{\mathbf{v}}_c-\mathbf{v}_{PCC}}=\frac{1}{R_f+L_f s} \tag{2}$$

The $\mathbf{v}_{PCC}$ is the measured voltage at the point of common coupling (PCC), the $\Delta\mathbf{v}$ is the difference between the $\hat{\mathbf{v}}_c$ and the $\mathbf{v}_{PCC}$, and the $R_f$ and $L_f$ are the parameters of the LC filter. The estimated line current $\hat{\mathbf{i}}_L$ is then used to control the ideal current sources in order to develop the simplified AC side model for the GSC as shown in Fig. 2. It is noted that due to the three-wire interconnection of the GSC, only two current sources are required while the current of phase c is a result of the combination of the other two phases ($\hat{\imath}_{Lc}=-\hat{\imath}_{La}-\hat{\imath}_{Lb}$).

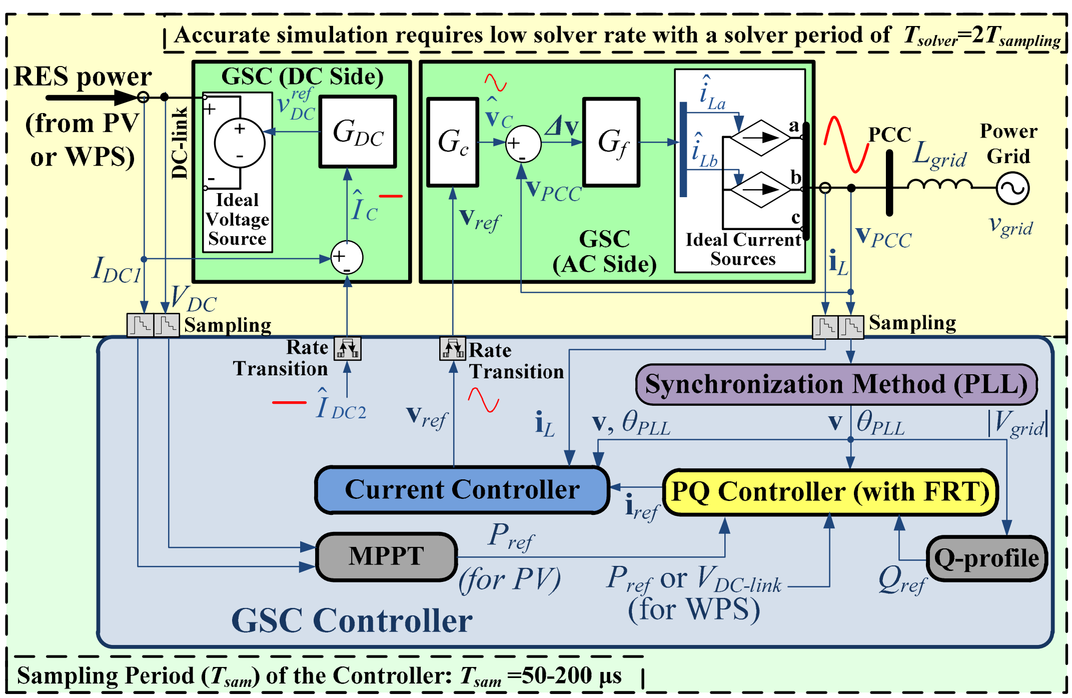

Fig. 2. Simplified and accurate model for a grid tied converter of a RES.

For the DC side of the GSC, the estimated DC-link voltage $\hat{V}_{DC}$, can be estimated through the charging/discharging current of the capacitor $C_{DC}$, as shown in Fig. 1. However, since the current $I_{DC2}$ contains high-frequency switching noise, it is first required to estimate this current through an average model. Thus, the estimated DC current $\hat{I}_{DC2}$ is given in (3) according to the fact that the active power ($P$) should be balanced on the DC and AC sides of the GSC.

$$\underbrace{P_{DC} = \hat{I}_{DC2} \cdot V_{DC},\ P_{AC} = \mathbf{v}_{PCC} \cdot \mathbf{i}_L,\ P_{DC} = P_{AC}}_{\Downarrow} \qquad (3)$$
$$\hat{I}_{DC2} = \frac{v_{PCCa} \cdot i_{La} + v_{PCCb} \cdot i_{Lb} + v_{PCCc} \cdot i_{Lc}}{V_{DC}}$$

The $\mathbf{v}_{PCC}=[v_{PCCa}\ v_{PCCb}\ v_{PCCc}]^T$ is the grid voltage at the PCC and the line currents $\mathbf{i}_L = [i_{La}\ i_{Lb}\ i_{Lc}]^T$ is the injected current into the grid. It is worth mentioning that the GSC losses have been considered negligible in this formulation. However, if the losses need to be considered, a GSC power losses modelling [17] can be used to enhanced the proposed model. The current $\hat{I}_{DC2}$ can then be used for estimating the voltage across the capacitor according to the transfer function $G_{DC}(s)$, as shown in (4), that describes the capacitor charging procedure.

$$G_{DC}(s) = \frac{\hat{V}_{DC}}{\hat{I}_c} = \frac{\hat{V}_{DC}}{I_{DC1} - \hat{I}_{DC2}} = \frac{1}{C_{DC} s} \qquad (4)$$

It is noted that the $I_{DC1}$ is the DC current that flows from the RES. Hence, the estimated capacitor voltage $\hat{V}_{DC}$ can then be replicated by the simplified model using an ideal voltage source as shown in Fig. 2. As a result, the DC side of the GSC can be accurately modeled without any switching signals.

It is worth highlighting that the proposed simplified models can use a simulator with a significantly smaller solver period ($T_{solver}$=0.5$T_{sam}$) compared to the detailed model due to the average estimation of all the switching signals.

In practical applications, the controller of the GSC is developed within the embedded micro-controller and is designed in discrete-time using fixed sampling rate. Therefore, it is essential to design the proposed simplified GSC model in discrete-time with fix step as well as shown in [18]. For achieving such a discrete-time model, the transfer function of (1), (2) and (4) need to be expressed in discrete-time by using the backward Euler method, as given in (5), (6) and (7) respectively.

$$\hat{\mathbf{v}}_c(k) = \frac{T_{solver}}{T_{solver} + T_{delay}} \cdot \mathbf{v}_{ref}(k) + \frac{T_{delay}}{T_{solver} + T_{delay}} \cdot \hat{\mathbf{v}}_c(k-1) \qquad (5)$$

$$\hat{\mathbf{i}}_L(k) = \frac{T_{solver}}{R_f T_{solver} + L_f} \cdot \Delta\mathbf{v}(k) + \frac{L_f}{R_f T_{solver} + L_f} \cdot \hat{\mathbf{i}}_L(k-1) \qquad (6)$$

$$\hat{V}_{DC}(k) = \frac{T_{solver}}{C_{DC}} \cdot \hat{I}_c(k) + \hat{V}_{DC}(k-1) \qquad (7)$$

$k$ represents the discrete time step and $T_{solver}$ is simulation's solver fix period. As a result, the use of (5)-(7) in a discrete-time EMT simulation software can enable the development of the simplified discrete-time models for the GSC.

## III. Evaluation of the Proposed GSC Modelling

For evaluating the simplified GSC model, both the detailed (Fig. 1) and the simplified/proposed (Fig. 2) models have been developed in MATLAB/Simulink. Both models have been developed using discrete-time fixed step solver. The simulation results are demonstrated in Fig. 3 under several operating conditions. Fig. 3 shows the PCC voltage $\mathbf{v}_{abc}$, the line currents $\mathbf{i}_{abc}$ and the DC voltage $V_{DC}$ as resulted by the detailed GSC simulation model (solid blue line) and the proposed simplified models (dashed green line). It can be observed in Fig. 3 that the simplified model achieves an accurate and dynamic operation under a 2 kVAr reactive power step at 0.05 s, a 4 kW active power step at 0.1 s, an unbalanced voltage sag event at 0.15 s, under intense low-order harmonic distortion at 0.2 s. Further, an advanced current controller with unbalanced and harmonic compensation module [14] is activated at 0.25 s and as a result a high quality and symmetrical current are injected by the GSCs. It is noted that under any condition, the proposed simplified GSC model achieves a 2% accuracy on the grid voltages, a 1% accuracy on the line currents and a 0.2% accuracy on the DC voltage.

It is worth to highlight that for the purposes of this paper, an exactly identical controller is designed with $T_{sam}$=100 μs for both models while the simulation runs with a solver period of 50 μs for the case of the simplified GSC and of 1 μs for the case of detailed GSC. The computational requirements of the two

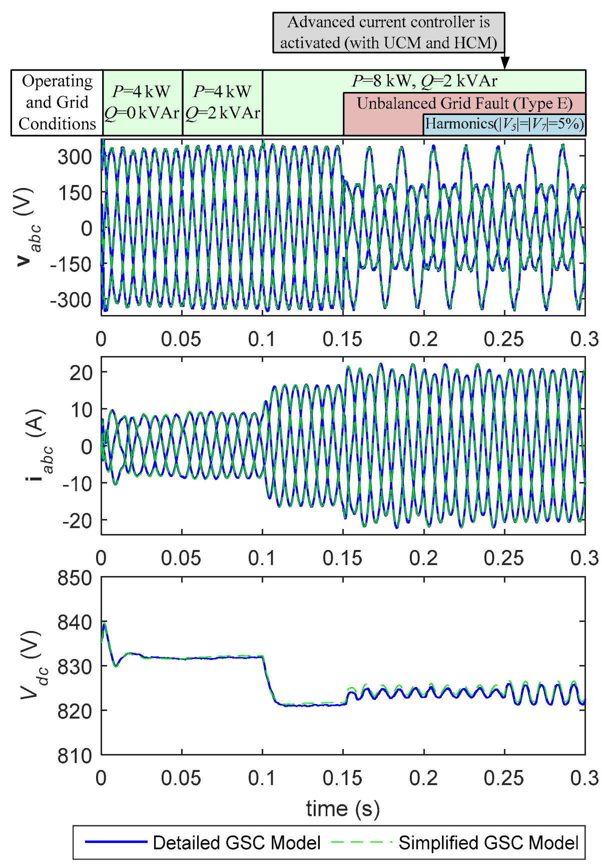


Fig. 3. Three-phase voltage and current and DC-link voltage of the detailed and the proposed simplified GSC model under different conditions.

models are evaluated using the Simulink Profiler Report, where it is shown that the proposed simplified GSC models runs 5.1 times faster than the analytical model.

## IV. Case Study - Impact of RESs on the Power Grid

A case study enabled by the use of the proposed simplified GSC models is presented in this section. A realistic distribution network (DN) is developed as shown in Fig. 4 with seven single and three-phase consumers (based on the line parameters used in distribution grid of Cyprus that are available to the authors by the Electricity Authority of Cyprus). In this DN, four rooftop PV systems are connected through the proposed GSC models as shown in Fig. 4. The integration of these PV systems transform the consumers 2, 3, 5, and 6 into prosumers, since they can simultaneously produce and consume energy. The computational efficiency of the proposed modelling allows to more efficiently investigate the interaction of several PVs with a realistic DN. In this case study, the low voltage level DN operation is evaluated when an unbalanced Type E [19], [20] fault occurs at the medium voltage level with 60% voltage sag in phase b and c. This low voltage fault is propagated into the low voltage feeder through the Wye-Delta MV/LV transformer. Due to the Wye-Delta transformer, the fault is propagated as Type F [19], [20] in the low voltage feeder. The results are summarized in Table I when: (a) all the RESs are disconnected, (b) all the RESs remain connected but without providing voltage support, (c) all the RESs provide positive sequence voltage support, and (d) RESs at buses 3 and 6 provide positive sequence FRT support while the RESs at buses 2 and 5 provide full negative sequence reactive support. According to this case study, the advanced FRT controllers of RES are properly evaluated and the impact of each control strategy can be properly evaluated for the entire DN. The advanced FRT operation of (c) (which is the FRT strategy currently required for RESs connected to medium or high voltage level) is beneficial for increasing the positive sequence voltage at the entire DN. In case of the FRT operation of (d), which imposes a novel support scheme for both the positive and negative sequence of voltage, the results show a compromise support where the positive sequence voltage is partially increased (for enhancing voltage stability) and the negative sequence is partially decreased (for balancing the asymmetries) of the DN.

A very important aspect is that the proposed simplified modelling of the GSC can be used for investigating the effect of several RESs on the power system, when operating according to advanced control schemes. In the case study of this section, the PV system of prosumer 5 is configured to operate according to a novel control technique under grid fault. As shown in Fig. 5, the GSC operation of prosumer 5 can operate in two different FRT modes: i) for providing reactive support

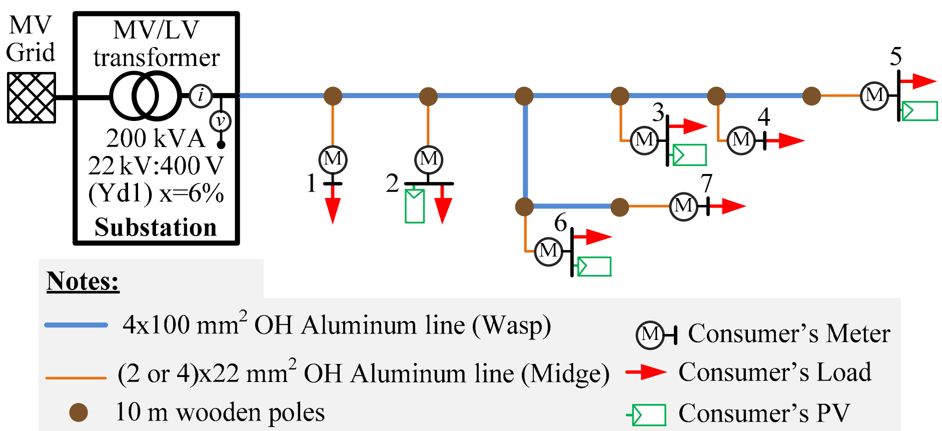


Fig. 4. Modeling of a DN with high penetration of RES using the proposed simplified GSC models.

TABLE I. Operation of the DN with RESs during a Grid Fault

| **Operation of RESs during a grid fault** | **Voltage at selected busses of the DN** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ***MV/LV transformer*** | ***Consumer 1*** | ***Prosumer 2*** | ***Prosumer 3*** | ***Consumer 4*** | ***Prosumer 5*** | ***Prosumer 6*** | ***Consumer 7*** |
| ***(a) RES disconnected*** | $\lvert v^+\rvert$=0.599 $\lvert v^-\rvert$=0.198 | $\lvert v^+\rvert$=0.593 $\lvert v^-\rvert$=0.195 | $\lvert v^+\rvert$=0.589 $\lvert v^-\rvert$=0.192 | $\lvert v^+\rvert$=0.584 $\lvert v^-\rvert$=0.190 | $\lvert v^+\rvert$=0.584 $\lvert v^-\rvert$=0.189 | $\lvert v^+\rvert$=0.583 $\lvert v^-\rvert$=0.189 | $\lvert v^+\rvert$=0.585 $\lvert v^-\rvert$=0.190 | $\lvert v^+\rvert$=0.585 $\lvert v^-\rvert$=0.190 |
| ***(b) RES without FRT support*** | $\lvert v^+\rvert$=0.601 $\lvert v^-\rvert$=0.199 | $\lvert v^+\rvert$=0.596 $\lvert v^-\rvert$=0.198 | $\lvert v^+\rvert$=0.593 $\lvert v^-\rvert$=0.200 | $\lvert v^+\rvert$=0.593 $\lvert v^-\rvert$=0.198 | $\lvert v^+\rvert$=0.591 $\lvert v^-\rvert$=0.198 | $\lvert v^+\rvert$=0.589 $\lvert v^-\rvert$=0.201 | $\lvert v^+\rvert$=0.594 $\lvert v^-\rvert$=0.197 | $\lvert v^+\rvert$=0.593 $\lvert v^-\rvert$=0.197 |
| ***(c)RES with positive sequence FRT*** | $\lvert v^+\rvert$=**0.611** $\lvert v^-\rvert$=0.198 | $\lvert v^+\rvert$=**0.608** $\lvert v^-\rvert$=0.195 | $\lvert v^+\rvert$=**0.608** $\lvert v^-\rvert$=0.192 | $\lvert v^+\rvert$=**0.608** $\lvert v^-\rvert$=0.189 | $\lvert v^+\rvert$=**0.609** $\lvert v^-\rvert$=0.189 | $\lvert v^+\rvert$=**0.608** $\lvert v^-\rvert$=0.188 | $\lvert v^+\rvert$=**0.608** $\lvert v^-\rvert$=0.189 | $\lvert v^+\rvert$=**0.608** $\lvert v^-\rvert$=0.190 |
| ***(d)RES with positive and negative sequence FRT*** | $\lvert v^+\rvert$=0.605 $\lvert v^-\rvert$=**0.192** | $\lvert v^+\rvert$=0.601 $\lvert v^-\rvert$=**0.187** | $\lvert v^+\rvert$=0.598 $\lvert v^-\rvert$=**0.182** | $\lvert v^+\rvert$=0.596 $\lvert v^-\rvert$=**0.176** | $\lvert v^+\rvert$=0.597 $\lvert v^-\rvert$=**0.178** | $\lvert v^+\rvert$=0.595 $\lvert v^-\rvert$=**0.174** | $\lvert v^+\rvert$=0.598 $\lvert v^-\rvert$=**0.178** | $\lvert v^+\rvert$=0.598 $\lvert v^-\rvert$=**0.179** |

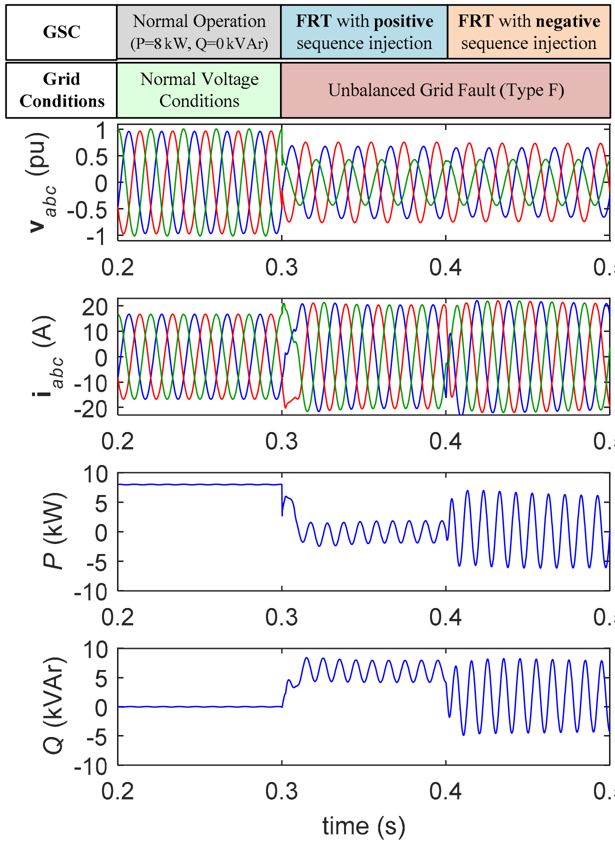


Fig. 5. FRT operation of the GSC of prosumer 5 under a grid fault.

with full positive sequence current injection (0.3 s < $t$ < 0.4 s) and ii) for providing reactive support with full negative sequence current injection (0.4 s < $t$ < 0.5 s) as suggested in [11], [14]. In the FRT operation of the GSC, a reactive current $I_Q = k(|V_n| - |\mathbf{v}_{PCC}|)$ is injected by the GSC according to the level of the voltage sag, where $k$ is set to 2 according to the grid regulations [2], $|V_n|$ is the nominal voltage amplitude, and $|\mathbf{v}_{PCC}|$ is the voltage amplitude at the PCC. In the first mode, the positive sequence reactive power support can increase the positive sequence of the voltage but it cannot minimize the voltage asymmetries (negative sequence). On the other hand, in the latter mode the voltage asymmetries are compensated but the positive sequence voltages are not essentially affected. These conclusions are also demonstrated in the results summarized in Table I, when the GSCs operate in different modes.

## V. Conclusions

This paper proposes a simplified, accurate, and computationally efficient modelling for the GSC of RESs. The proposed model can realistically track the operation of the GSC under any grid conditions. The computational efficiency of the model allows the detailed investigation of the interaction between several RESs and the power system. In this investigation advanced control techniques can be used for the GSC and their effect on the entire power grid can be more properly evaluated.

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